

Measuring Soil Moisture with Radio-waves

Undergraduate Honors Thesis

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## Abstract

Soil moisture has been linked to many pressing environmental issues, but due to the large natural variability in soil texture, there is no efficient way to observe the spatial (horizontal and vertical) and temporal dynamics on a large scale. This study will focus on using radio-frequency identification (RFID), technology in an effort to expand the scale on which soil moisture can be measured. Application of RFID sensors allows for a cheap, wireless, powerless system that could be deployed across large area.

Current progress in this study has demonstrated a noticeable correlation between the received signal strength and the moisture content of the soil using radio frequencies of 902-928 MHz. It is anticipated that through further research, using RFID readers that have a received signal strength indicator (RSSI), soil moisture can be measured accurately and efficiently. This paper will discuss results from experiments that observe the effects that confounding variables such as separation distance between the reader and sensors, soil moisture, and depth of the soil have on radio waves.

## Acknowledgement

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## Table of Contents

Abstract.....	1
List of Figures .....	5
1.0 Introduction .....	6
1.1 Environmental Impact.....	6
1.1.1 Natural Disasters.....	7
1.1.2 Agricultural Hazards.....	7
1.1.3 Environmental Variables.....	7
1.2 Temporal and Spatial Data.....	8
1.2.1 Growth vs. Cost Analysis.....	8
1.3 Precision Agriculture .....	9
1.3.1 Soil Sensors .....	10
1.3.2 Tractor Sensors .....	12
1.3.3 Drones.....	12
1.3.4 Satellite .....	14
1.3.5 Radio Frequency .....	15
1.3.5.1 Energy Loss (Attenuation).....	16
2.0 Methodology .....	16
2.1 ALR-9680 .....	17
2.1.2 Proof of Concept.....	17
2.1.2 Comparison to soil moisture sensor.....	18
2.1.3 Multiple Tag Test .....	22
2.2 ALH-9011.....	24
2.2.1 Effect of Angle and Distance on RSSI .....	24
2.2.2 Depth of Soil to Tag.....	25
2.2.3 Depth of Water to Tag .....	26
2.2.4 Soil and Water Depth Combination.....	27
3.0 Conclusion .....	28

## List of Figures

FIGURE 1: SYSTEM ARCHITECTURE (GARCIA-SANCHEZ ET AL. 2011) .....	10
FIGURE 2: MULTISPECTRAL IMAGE FROM UAV (TILMAN ET AL. 2002) .....	14
FIGURE 3: ALIEN TECHNOLOGY ALN-9741 RFID TAG .....	15
FIGURE 4: RSSI VALUES MEASURED BY THE ALR-9680 THROUGH A PLASTIC CONTAINER AS THE CONTAINER WENT FROM EMPTY TO FILLED WITH WATER. ....	18
FIGURE 5: SOIL MOISTURE MEASURED WITH THE DECAGON 5TE AS 100 ML OF WATER WAS ADDED EVERY 30 SECONDS INTO THE SOIL COLUMN. ....	19
FIGURE 6: RSSI VALUE MEASURED WITH THE ALR-9680 AS 100 ML OF WATER WAS ADDED EVERY 30 SECONDS INTO THE SOIL COLUMN. ....	20
FIGURE 7: CORRELATION BETWEEN RSSI VALUES MEASURED WITH THE ALR-9680 VERSE THE SIMULTANEOUS SOIL MOISTURE READING FROM THE DECAGON 5TE WITH A TREND LINE. ....	21
FIGURE 8: CORRELATION BETWEEN RSSI MOVING AVERAGE WITH THE ALR-9680 VERSE THE SIMULTANEOUS SOIL MOISTURE READING FROM THE DECAGON 5TE WITH A TREND LINE. ....	21
FIGURE 9: THE MOVING AVERAGE OF EACH ALN-9741 AS 100 ML OF WATER WAS ADDED EVERY 30 SECONDS TO THE CONTAINER. ....	23
FIGURE 10: RSSI VALUES MEASURED BY THE ALH-9011 AS THE ANGLE AND DISTANCE CHANGE. ....	25
FIGURE 11: RSSI VALUES MEASURED USING THE ALH-9011 AND THE ALN-9741 AS THE LEVEL OF SAND ON TOP OF THE TAG INCREASED. ....	26
FIGURE 12: RSSI VALUE MEASURED USING THE ALH-9011 READER FOR BOTH THE H2O PROTOTYPE TAG AND THE ALN-9741 AS WATER WAS POURED ON TOP OF THE TAG IN A CONTAINER. ....	27
FIGURE 13: RSSI VALUE MEASURED USING THE ALH-9011 AND THE ALN-9741 FOR DIFFERENT SATURATION LEVELS AND VARYING DISTANCES ABOVE THE TAG. ....	28

## 1.0 Introduction

Soil moisture is a critical variable that impacts many environmental phenomenon including climate change (Lu et al. 2013), agriculture, and natural hazards such as floods and landslides. The most common application of soil moisture in everyday life worldwide relates to agricultural practices. In 2012, an estimated 5 billion acres of land was used globally to produce nearly 17.4 trillion tons of crops (FAO, 2012). It is simple to see how any factor relating to the field of agriculture can be vital. Soil moisture plays a significant role in agriculture through its impact on runoff, infiltration, and vegetation (Wagner et al. 2003; Pastor and Post 1986). With a better understanding of these three factors, it is believed farmers can produce larger crop yields at a lower cost (Siden et al. 2007) and lower levels of input, which has given way to the field of precision agriculture. This paper will evaluate methods used in precision agriculture in terms of their impact on soil moisture as well as suggest new methods in detecting soil moisture through technology such as radio frequency identification devices (RFID).

## 1.1 Environmental Impact

Soil is everywhere from one's backyard to the bottom of the ocean. It has a large impact on everyone's daily life whether recognized or not. Soil is not only a building block for society, but it can also be a huge detrimental factor in society as well. That is why it is important to learn as much as possible about real time soil properties. There are no two scenarios where the role of soil moisture is more evident than in natural disasters and farming.



### 1.1.1 Natural Disasters

As mentioned above, soil plays a large role in many natural disasters. Some of the more obvious examples are landslides and floods (Entekhabi et al. 2010). For example, landslides occur when soil on a slope becomes completely saturated by rainfall. With more frequent soil moisture measurements, an area in potential danger of a landslide can be notified ahead of time when saturation levels become too high. Flooding also occurs typically during heavy rainfall when the rain is unable to infiltrate the soil at a rate greater than or equal to the rate at which it falls. Not all floods or landslides can be prevented by real-time analysis of the soil moisture, but this analysis could help with notifying the public of natural disasters ahead of time.

### 1.1.2 Agricultural Hazards

Typically, soil runoff is not a large problem, but when that runoff contains chemicals from fertilizer, pesticides, herbicides, or other pollutants on the ground, environmental problems can occur. Agriculture runoff is one of the largest contributors of nitrogen and phosphorus pollution in the country (US EPA 2016). There is no case more apparent than the Lake Erie algal blooms. In that particular case, nitrogen and phosphorus entered the watershed through runoff from farmlands. After heavy rainfall, the chemicals worked their way through the watershed and into Lake Erie, causing toxic green algae to cover large sections of the lake. In addition to being an environmental pollutant, the chemicals that are washed away in runoff are a waste of resources for the farms. This has given way to the study of precision agriculture.

### 1.1.3 Environmental Variables

The goal of precision agriculture is to find the optimal value of every variable - from soil moisture to nutrients levels - in order to maximize crop yield. Thus, one of

the biggest questions in efficient farming is finding the proper moisture content for each field. The dilemma for soil moisture is that “not enough” moisture means that plants are unable to absorb adequate nutrients, while “too much” moisture causes anaerobic conditions. When considering the difficulties of taking large data inputs in fields, there are two important factors that come into effect: temporal and spatial data.

## 1.2 Temporal and Spatial Data

Since the goal of precision agriculture is to create more efficient farming practices, then real-time decisions will need to be made based on real-time data collection. For farms, that means two forms of information are needed.

The first is temporal data. Precise decisions on how much to water crops cannot be made based on data collected the month before because too many variables could have changed during that time. When deciding how much water is needed, data at a higher temporal resolution will allow for better decisions.

The second form of information is spatial data. With over 5 billion acres of farmland, each square foot of farm land can be made up of different soil types, elevations, and compaction levels. Since so many aspects can change on large farms, it is important that information comes from all these different regions. Without spatial data, sections that may need a lot of attention, would only receive the same level of inputs as other, less-needy sections, thus decreasing yield.

### 1.2.1 Growth vs. Cost Analysis

The struggle for precision agriculture is not finding ways to measure spatial and temporal data, but finding a cost-efficient way for large farms to do so simultaneously

(Owe, Jeu, and Walker 2001). Since tractors, drones, and soil sensors can be expensive and do not provide the most precise data in terms of spatial and temporal information, a new way to study soil moisture is needed for farms as well as regions in risk of natural disasters. That technology could be radio frequency.

### 1.3 Precision Agriculture

One application where soil moisture is of the utmost importance is agriculture. In agriculture, as in any industry, the goal is to produce as much as one can while lowering the expense to do so. This is accomplished by maximizing crop yield while minimizing the input variables, such as fertilizer and water, that a farmer needs to apply to the field. The study of how to minimize inputs and maximize crop yield has come to be known as precision agriculture. The study of precision agriculture not only benefits the farming industry's profit margin, but also has environmental applications. For instance, if a farm is under-watered, then transpiration cannot occur, and plants are unable to absorb nutrients, which then means the plants are incapable of growing. However, if farmlands are overwatered, then the excess water may not infiltrate the soil, leading to surface runoff. Runoff has many negative impacts for the environment, such as erosion and flooding, but the most prominent in agriculture is nutrient runoff. Nutrient runoff is where chemicals from fertilizer, herbicides, and pesticides that have not yet been absorbed are washed away downstream. Nutrient runoff has been linked to algal blooms invading freshwater areas, contaminated water, and undernourished crops.

### 1.3.1 Soil Sensors

The first method which does the best job at recording all the necessary information at a fast rate is the use of wireless sensors. These are sensors planted in the ground at different depths to transmit the necessary information to a central location. With enough sensors, this allows for effective management zone data collection, and this data can be recorded any time as frequently as deemed necessary. A diagram of a possible layout can be found below in Figure 1. This diagram depicts a three field layout in which each field has sensors that communicates to a transmitter, which then conveys that data to a larger transmitter before being sent to a central data system. This diagram also shows the use of cameras to watch over the fields for any natural disturbances such as animals wandering the fields.

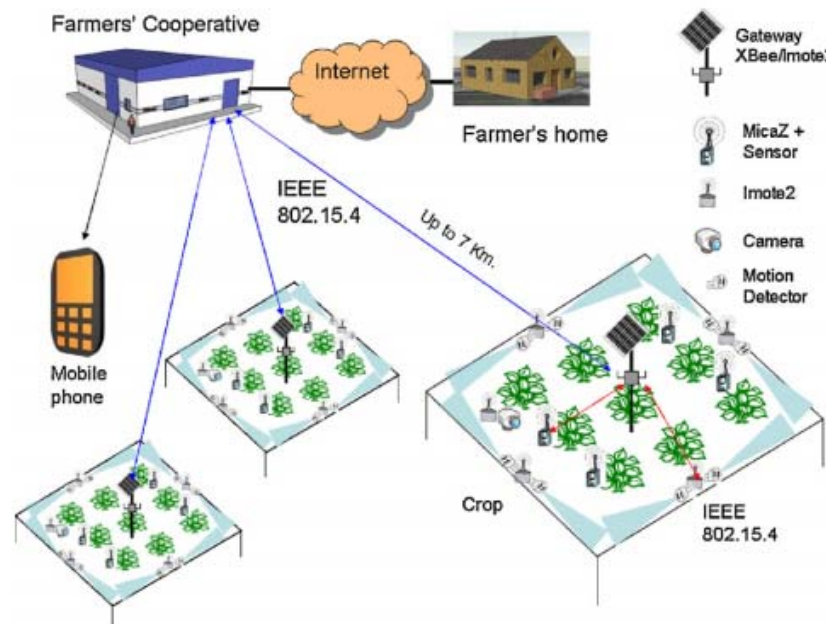


Figure 1: System Architecture (Garcia-Sanchez et al. 2011)

There is a large assortment of sensors available, but the main ideas are electrical and electromagnetic, optical and radiometric, and electrochemical sensors. Electrical and electromagnetic sensors are the most commonly used sensors in precision agriculture because of the information they are able to determine along with their robust and low cost design (Adamchuk et al. 2004) compared to other soil sensors. Electrical and electromagnetic sensors are capable of determining the soil texture, organic matter content, soil moisture content, salinity content, soil variability at various depths, nitrogen content, and cation ion exchange capacity, while allowing for direct inputs for existing prescription algorithms.

Other types of sensors include optical and radiometric sensors which detect energy levels absorbed or reflected by different soil particles. These sensors are capable of measuring soil pH levels, unlike the electrical and electromagnetic sensors, but cannot detect difference in soil depth.

Another sensor concept that has some benefits are electrochemical sensors, which emit a voltage corresponding to specific ions, meaning that electrochemical sensors can supply information on a larger number of macronutrients nutrients than the electrical or radiometric sensors. This is helpful in determining the amount of different brands of fertilizer that need to be applied.

There are several drawbacks to the implementation of soil sensors as they require a large amount of work to set up. To determine the variability of soil at different root depth and track the differences, the sensors need to be located on top of each other. Each sensor also needs to be connected to a data logger (could be wired

or wireless). Additionally, this can become an expensive method even with the incorporation of management zones since each zone will need multiple sensors. On large farms even the cheapest of the above sensors will add up to costing a large sum.

### 1.3.2 Tractor Sensors

A method that collects spatial data with high spatial resolution but poor temporal resolution is the use of tractors already being driven across farms. These vehicles can utilize manned or unmanned technologies guided by GPS. The benefit to this method is that nowadays many farms are too large to take care of by hand, so tractors are already readily available - saving a large startup cost. They collect data with the use of radiometric sensors that use gamma-rays to capture the radiometric isotopes in the soil as they travel over the land (Stockmann et al. 2015). This data serves two purposes as it can be synced to a central database for future analysis but can also simultaneously communicate with the tractor to apply the proper amount of fertilizer or water to each individual plant. The problem with this method is that tractors are not out driving all day collecting data, but are only driven at specified intervals when deemed necessary based on old data. This prevents inputs from being applied at the precise time needed since temporal resolution is low. There are several companies including Raven and Trimble that are currently working on this method for their profit.

### 1.3.3 Drones

In order to maintain high resolution for both temporal and spatial data farmers have to record this data continuously to know how quickly each crop needs to be replenished with nutrients and water. This is a tedious and expensive task using

tractor sensors and driving over every inch of a farm. Instead, unmanned aerial vehicles (UAVs) can fly over the land in between drive times. UAVs are advantageous because they can be flown over large farmlands in less time and more frequently than tractors can be driven across. This research is still in its beginning stages but shows promise moving forward (Hedley 2015).

So far the research has used multispectral sensors which interpret the infrared colors transmitted by nature. Figure 2 below is a multispectral image taken by a UAV. Red areas on the zone map indicate areas that do not need attention, where green areas indicate areas where plants are stressed. As UAV research is in its infancy there are still some problems that need to be sorted out. The biggest problem is that the resolution on these cameras that are flying anywhere from 100 to 2000 feet is poor compared to soil sensors on the ground. Another problem is that the path the UAVs take is typically inefficient. On modern tractors, farms use auto steering GPS technology which, when harvesting with a 60-foot plow, only overlaps by a couple inches each cut. UAVs cannot make this precise of a cut and therefore are wasting valuable time in the air when they only have flight times of 30 to 60 minutes.

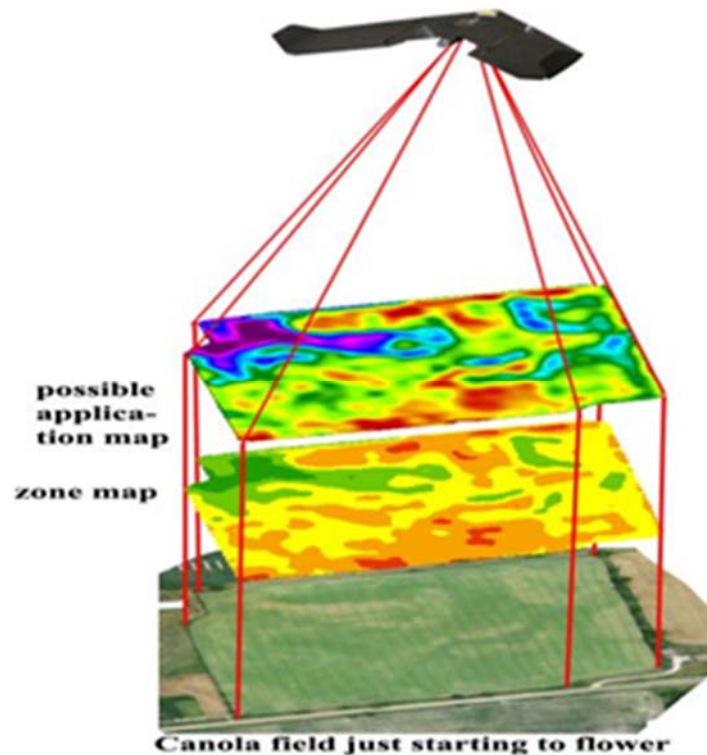


Figure 2: Multispectral Image from UAV (Tilman et al. 2002)

#### 1.3.4 Satellite

Similar to the UAV are satellites, which use multispectral sensors to capture wavelengths reflected off the Earth's surface. One of the main differences between the two however, is that satellite imaging of land has been around since the early 1970s. In fact Landsat 1 was launched in 1972 with a return time of 18 days, a spatial resolution of 80m and only four infrared bands (Mulla 2013). Today there are satellites that exist for commercial purposes such as the WorldView 2 satellite with 46cm panchromatic resolution, 1.85 meter multispectral resolution, 1.1 day return times and eight bands. WorldView 2 is able to collect images in the standard blue, green, red and near infrared but can also collect in purple, yellow, red-edge and another near infrared frequency. A WorldView 3 satellite was just launched in August of 2014 with resolution up to 31 cm panchromatic, 1.24 meter multispectral and 3.7 m



shortwave infrared, all with less than a 1 day return time. These satellites are good for crop pattern/type mapping and when combined with real-time remote sensing data can help decision making in precision agriculture. One of the major problems with satellites is that they are unable to help on cloudy days, leaving larger gaps in temporal data, especially when mixed with the already poor spatial data.

#### 1.3.5 Radio Frequency

There are several methods for maintaining either spatial or temporal data, such as soil sensors which take readings at all times for temporal data or tractors with sensors driving over an entire field for spatial data. However, there is no method currently in use for recording both sets of data that is cost effective as well as efficient. RFID tags may help with this issue. An RFID is simply a transponder/antenna; a microchip is attached to the antenna and comes encapsulated for protection. See Figure 3 for a common RFID picture. For identification purposes, RFIDs work similarly to a barcode, except RFIDs do not require a line of sight. In fact, RFIDs can be read not only from a distance, but through material such as soil in a field of corn, which makes them ideal for precision agricultural purposes.



*Figure 3: Alien Technology ALN-9741 RFID Tag*

Another benefit is that there are multiple types of tags such as active and passive tags. The latter is desirable for field measurements because the sensors are only activated when a RFID reader emits the desired radio frequency, so there is no

battery necessary and therefore no limit on the lifespan of these tags. There are three classifications of frequency at which passive RFIDs can work: low frequency (30 to 300 kHz), high frequency (3 to 30 Mhz), and ultra-high frequency (300 MHz to 3 GHz) (Violino 2005). Since the goal is to measure attenuation of the signal through the soil, the key is to choose a frequency which is susceptible to energy loss and has a long read range (Soontornpipit et al. 2006). What makes RFIDs more desirable for the field of precision agriculture is that they are compact so they do not disturb the soil and they are very cheap, costing as little as a nickel per device - almost nothing compared to most soil moisture sensors on the market, which cost around \$250 per sensor.

#### 1.3.5.1 Energy Loss (Attenuation)

One limitation to the tags is that there can be signal interference by either signal deflection or a loss of signal strength as the radio-waves try to pass through various materials. In most industries, if there is a chance the signal might have to pass through water, many manufacturers do not recommend using RFIDs. This is because water absorbs the radio-waves at a much higher percentage than most solid materials.

Signal strength is not only affected by the moisture content of its surroundings, but by everything the signal passes through on its path to the reader. A key to this study will be to finding the different levels which different soil types affect radio signal strengths.

## 2.0 Methodology

The experimental procedures are designed around variables that could affect the signal strength of the returning radio waves. Each experiment was designed

around a specific variable in an effort to isolate the effect one may or may not have. These experiments were broken down into the following: (a) proof of concept, (b) comparison to soil moisture sensor, (c) multiple RFID tag test, (d) reader to tag air distance and angle test, (e) depth of soil to tag test, (f) depth of water to tag test, and (g) soil and water depth combination test.

Sand was used for this initial test since among soil types sand presents the highest hydraulic conductivity. A polyvinyl chloride (PVC) soil column of 6-inch inside diameter was chosen as the testing equipment for initial tests because it was the minimum size piping that provided a large enough volume for the Decagon 5TE soil moisture sensor with a sample measurement volume of 0.7 L (“Soil Moisture Sensors | Volumetric Water Content Sensors | Decagon Devices” 2016).

Two types of RFID readers were used for collecting data as there is some difference in how they collect and store data. The first reader was an Alien Technology ALR-9680 which is a stationary unit that was used for initial experiments to capture continuous, automatically-logged RSSI values. For this reader, the higher the RSSI value, the stronger the signal strength, and theoretically, the lower the soil moisture. The first experiment was a proof of concept test.

## 2.1 ALR-9680

### 2.1.2 Proof of Concept

For this experiment the soil column started completely empty with one RFID tag attached on the back and placed 3 feet away from the reader. A baseline RSSI value was then recorded for 65 seconds at one second intervals. Once the baseline

measurements were complete, the container was completely filled with water and once again the RSSI values were recorded for 60 seconds at one second intervals. This test was completed for ALN-9741 Alien Technology RFID Tags. As can be seen in the results below in Figure 4, once water was added at the 65 second mark, the RSSI values quickly decreased from an average of 92 all the way down to an average of 69. This indicates that there is potential for RSSI values to be used to indicate soil moisture content since the addition of water has noticeable impacts on the RSSI values.

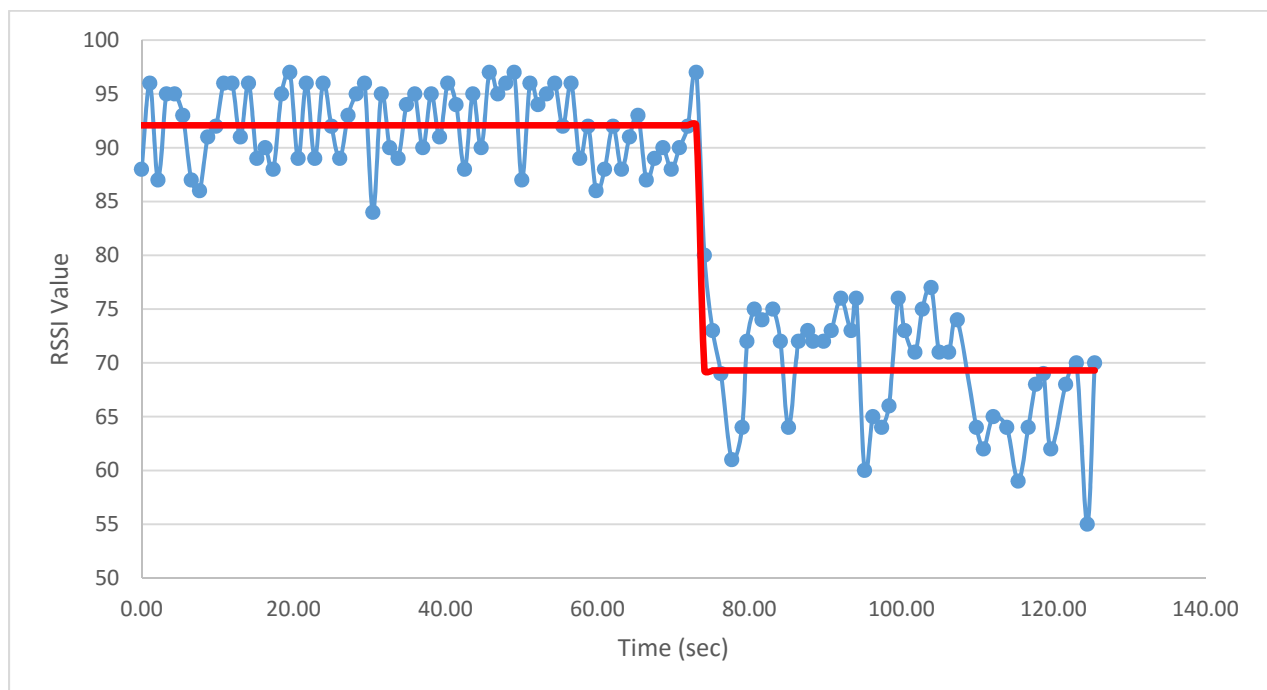


Figure 4: RSSI values measured by the ALR-9680 through a plastic container as the container went from empty to filled with water.

### 2.1.2 Comparison to soil moisture sensor

After the proof of concept test demonstrated a possible relation between moisture and RSSI values, the next step was to test the correlation between the RSSI

value and previously used soil moisture sensors. The sensor used for this experiment was the Decagon 5TE soil moisture sensor, which was vertically aligned and placed in the exact center of the soil column. Once the RFID tag and soil moisture sensor were in place, water was added at 100 mL every 30 seconds.

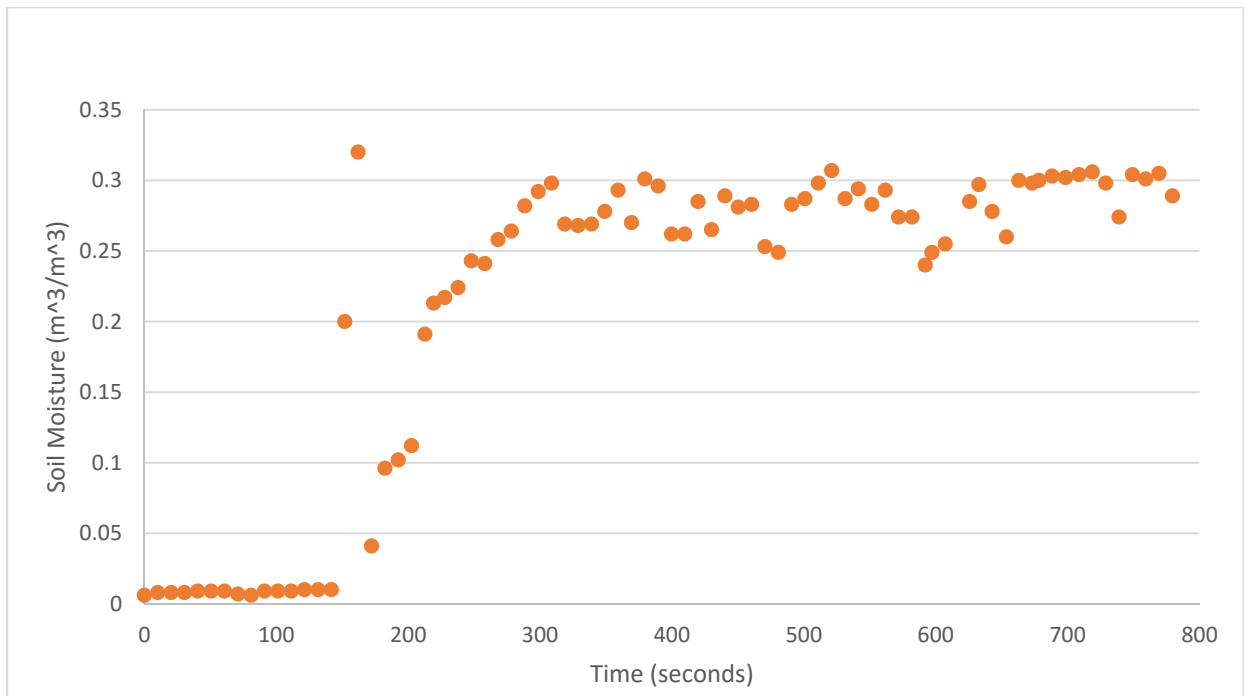


Figure 5: Soil moisture measured with the Decagon 5TE as 100 mL of water was added every 30 seconds into the soil column.

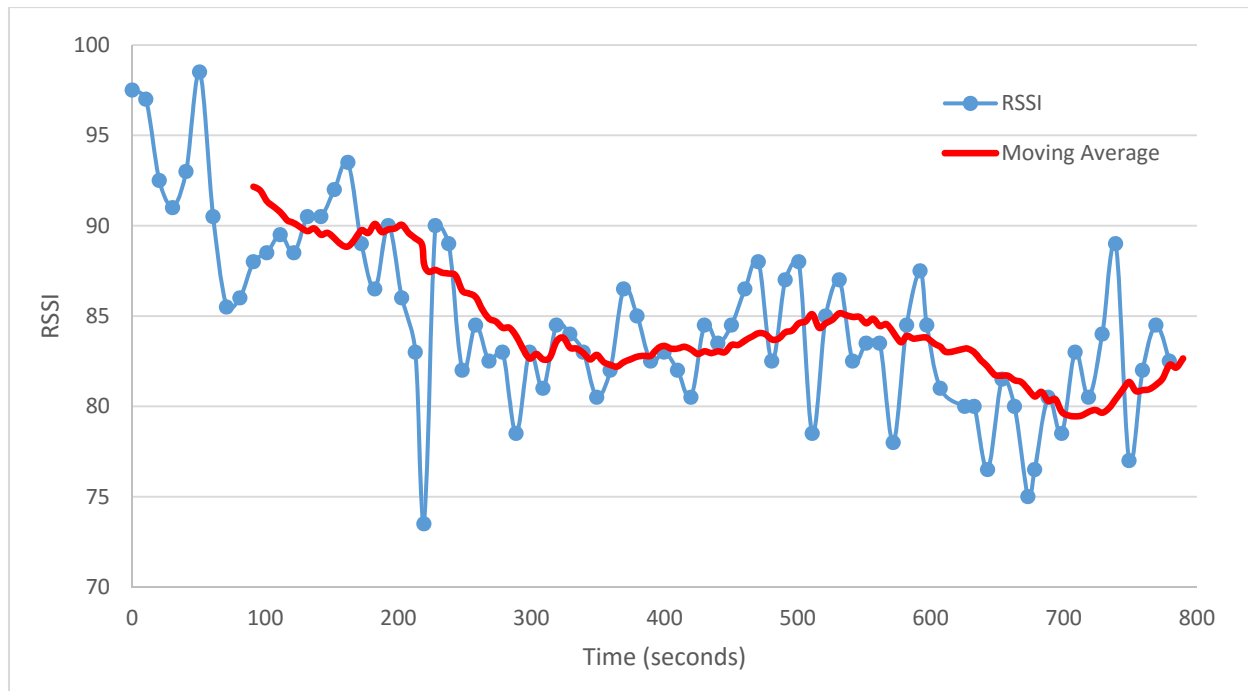


Figure 6: RSSI value measured with the ALR-9680 as 100 mL of water was added every 30 seconds into the soil column.

The soil moisture sensor reading was taken every 10 seconds while the RSSI value was taken every 5 seconds. In Figure 5 below, the soil moisture recorded by the Decagon 5TE sensor can be seen and in Figure 6, the RSSI value recorded by the ALR-9680. In Figure 6, the red line represents the moving average of the RSSI value over the course of the whole test. In general, as the soil moisture increases, the RSSI value decreases though there are several outliers. These outliers are most likely caused by the noise of the radio signal and imperfection of the RSSI reading.

Soil moisture began to rapidly increase after 150 seconds with the Decagon 5TE sensors, but the RSSI value's moving average gradually changed through the entire experiment runtime as can be seen in Figure 6 by the red line. This indicates that the soil moisture sensor works more as a point analysis because of the rapid increase which, once it becomes saturated, levels off, whereas the RSSI value, fluctuates more

and begins decreasing initially. This indicates that RSSI may be more dependent on the total soil moisture as opposed to just a single point.

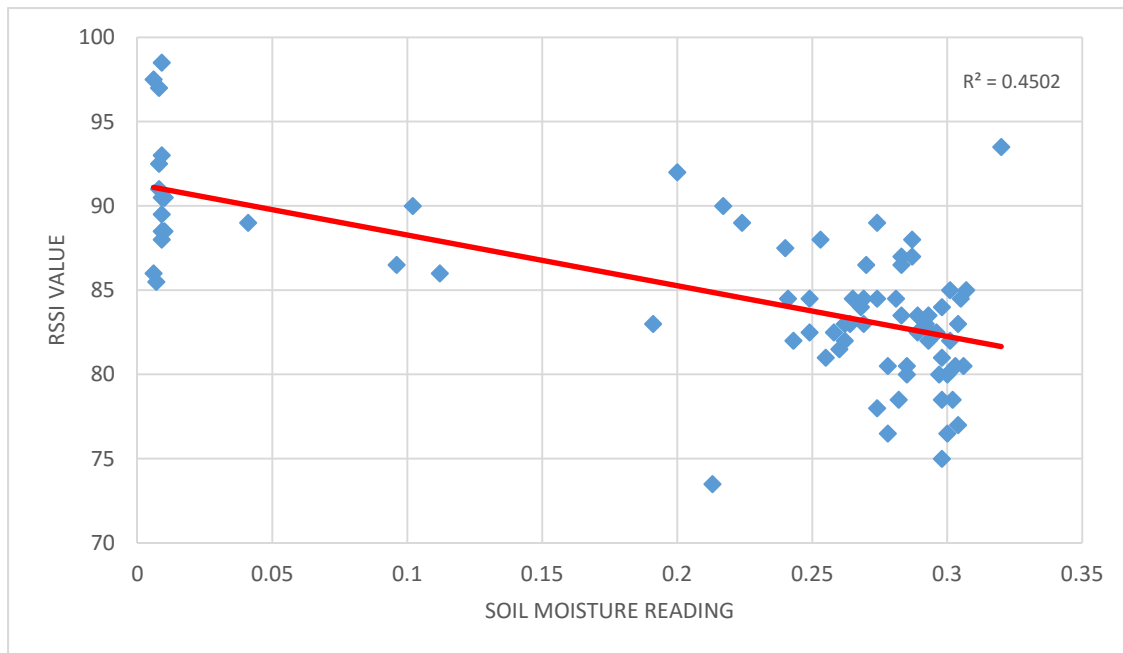


Figure 7: Correlation between RSSI values measured with the ALR-9680 verse the simultaneous soil moisture reading from the Decagon 5TE with a trend line.

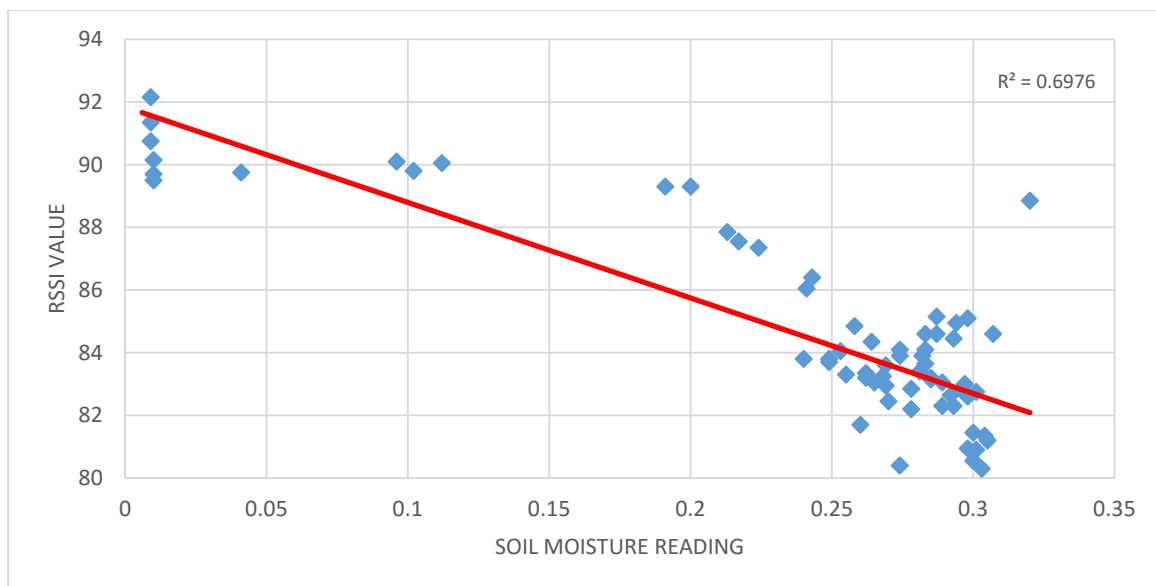


Figure 8: Correlation between RSSI moving average with the ALR-9680 verse the simultaneous soil moisture reading from the Decagon 5TE with a trend line.

Figure 7 above shows the correlation between the RSSI and soil moisture measurements. With a correlation coefficient of just over 0.4502, there is not a tight

correlation partially because of the gap in the soil moisture data, but there is a loose visible trend. Figure 8 represents the moving average of the RSSI values over the span of the entire test. This eliminates some of the noise from and imprecision of the ALR-9680 and has a correlation coefficient of 0.6976 with the Decagon 5TE.

### 2.1.3 Multiple Tag Test

The final test with the ALR-9680 involved taking readings for 8 sensors repeatedly over 500 seconds. For this test, the tags were placed to the back of the soil column spaced one inch apart. The soil column was filled with nine inches of sand to cover all of the tags. Once covered, RSSI values were collected and recorded through the use of Alien Gateway every five seconds, while every 30 seconds 100mL of water was added to the top of the soil column. This test was designed to observe RSSI values as saturated the soil column. Initially, the water infiltrated quickly through upper layers of the soil and saturated the bottom layers. In Figure 9 below, the moving average of the ten previous data points is shown for the RSSI values of all eight tags. The tag on the top four layers quickly drop in their RSSI values as the sand in the upper regions of the soil column are introduced to water first. Then as the tags at the bottom of the column are introduced to water their signal strength drops as well.



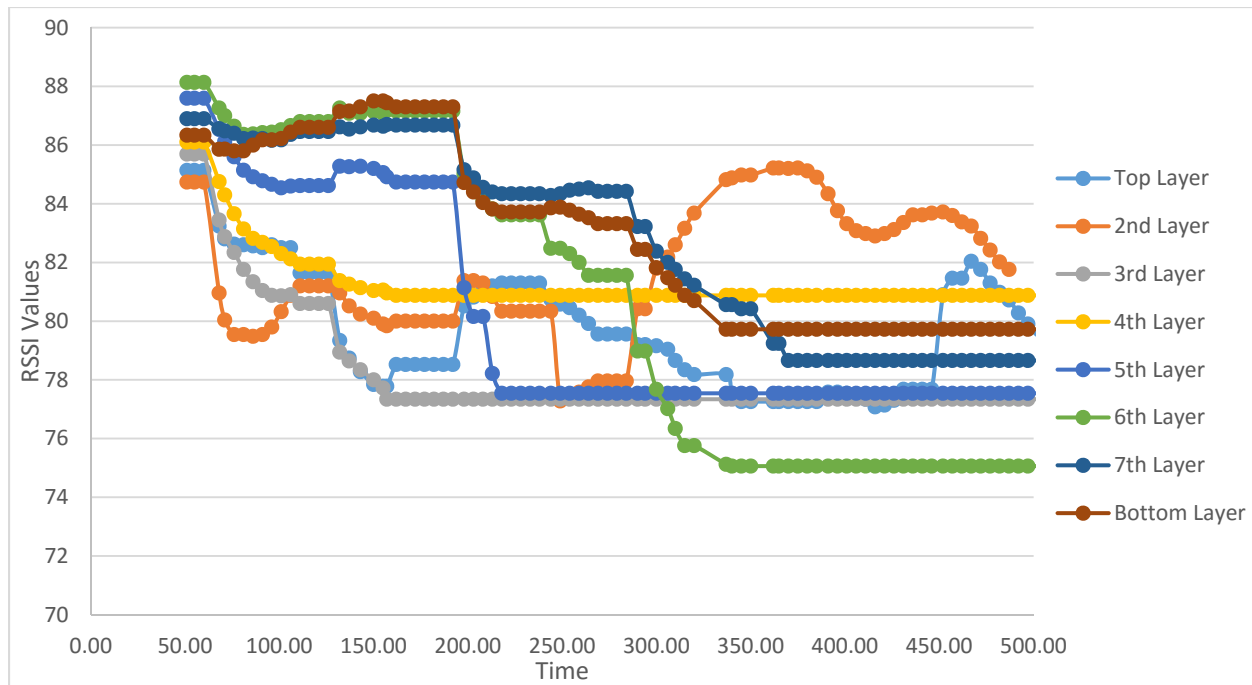


Figure 9: The moving average of each ALN-9741 as 100 mL of water was added every 30 seconds to the container.

The second RFID reader was the ALH-9011 handheld reader. This reader was designed for mobility and thus made it easier to determine how changes in distance effected the signal strength. However, it is unable to store RSSI values for multiple tags, so all tests could only be conducted on one tag at a time for data collection purposes. This reader was used for experiments d, e, f and g. This specific reader has a maximum RF power of 30.0 dBm, which all tests were conducted at. Additionally, this reader reports RSSI values in the form of negative numbers. So the lower the value, the weaker the signal strength. The reader was unable to detect the signal strength of any RSSI value below -70. For all data which the signal strength was too weak, a value of -70 was used.

## 2.2 ALH-9011

### 2.2.1 Effect of Angle and Distance on RSSI

The first test conducted with the handheld RFID reader was a test to observe attenuation through air at different angles and distances. This was conducted by placing an ALN-9741 tag perpendicular to the ground in a spacious setting in order to avoid multipath errors. Once that was set up, five readings were taken at all combinations of angles and distances for which the distances were 1, 2 and 3 feet and the angles were 15 degree increments between 0 and 90 degrees. The reader was positioned at each of these locations at the same height as the tag and facing parallel to the tag. The data for this experiment can be seen in Figure 10. Not all angle and distance combinations registered RSSI values on the ALH-9011 reader. Those values are depicted in grey in Figure 10. It can be noted that as the angle increased from 0 to 90 degrees the RSSI value decreased. Additionally, as the distance increased, the RSSI value decreased. This indicates that the signal strength was weaker for the greater the distance of the measurement and the greater the angle.

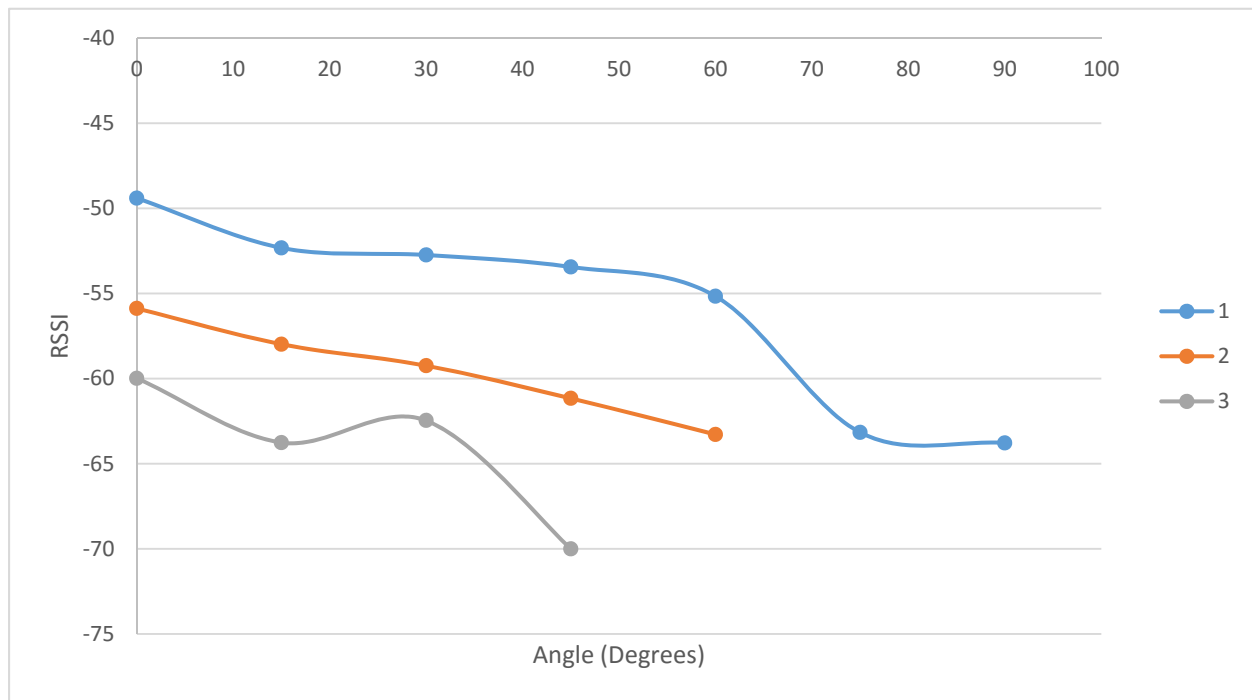


Figure 10: RSSI values measured by the ALH-9011 as the angle and distance change.

### 2.2.2 Depth of Soil to Tag

After the angle and distance was conducted through the air, the tag was tested in soil. The tag was buried at the center and bottom of a 14.5" tall container that was 11" in diameter. The container was initially empty and was then filled with one inch increments of sand until there were eight total inches of sand in the container. The RSSI value through the sand was measured by averaging five readings every time one inch of sand was added to the container. The reading was taken from 12 inches above the bottom of the container. In Figure 11, there was an unpredicted upward trend in terms of the RSSI value when more sand was added.

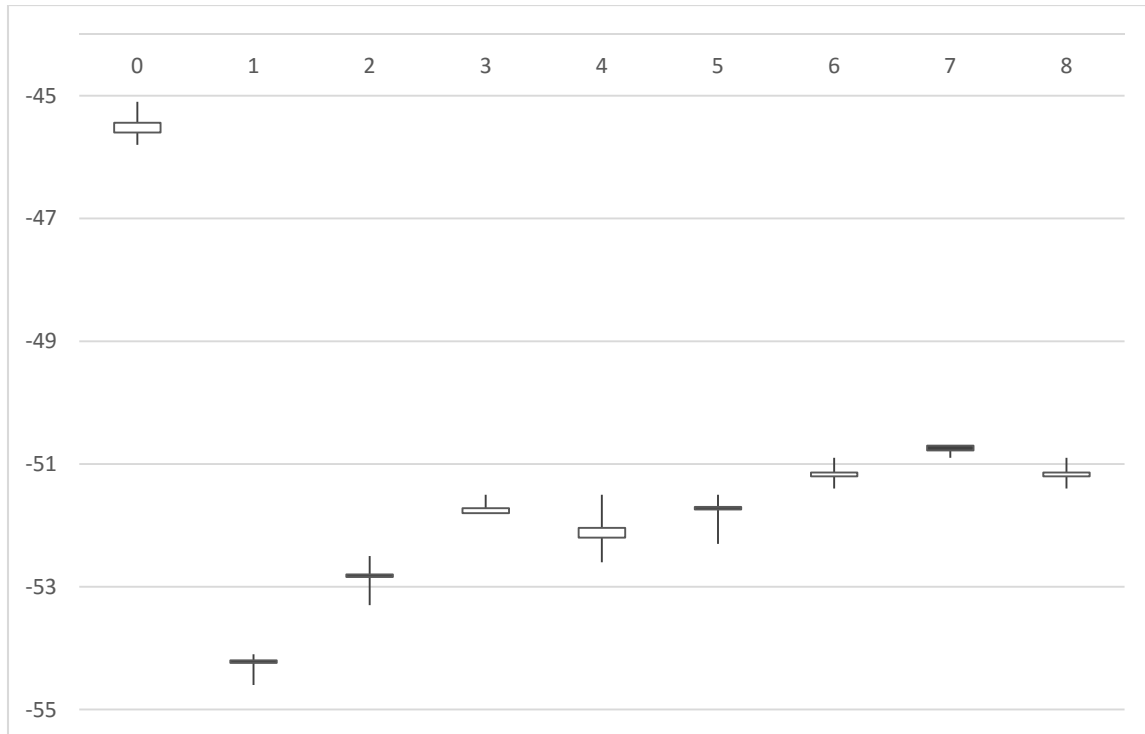


Figure 11: RSSI values measured using the ALH-9011 and the ALN-9741 as the level of sand on top of the tag increased.

### 2.2.3 Depth of Water to Tag

After the soil depth test, a test was conducted to determine the effect of the amount of water on the RSSI using a similar procedure to that of the soil depth test, but replacing the addition of soil with the addition of water. The results can be seen in Figure 12.

In general the results indicate that the more water that the radio signal is required to pass through, the weaker the returning signal strength. The results do not follow a predictable pattern, as instead of always decreasing in value there are some increases with the addition of water. Between the two tags, the ALN-9741 had a much stronger signal throughout the test than the H<sub>2</sub>O prototype tag and also followed a more consistent decreasing trend. Thus the ALN-9741 was used for further testing.

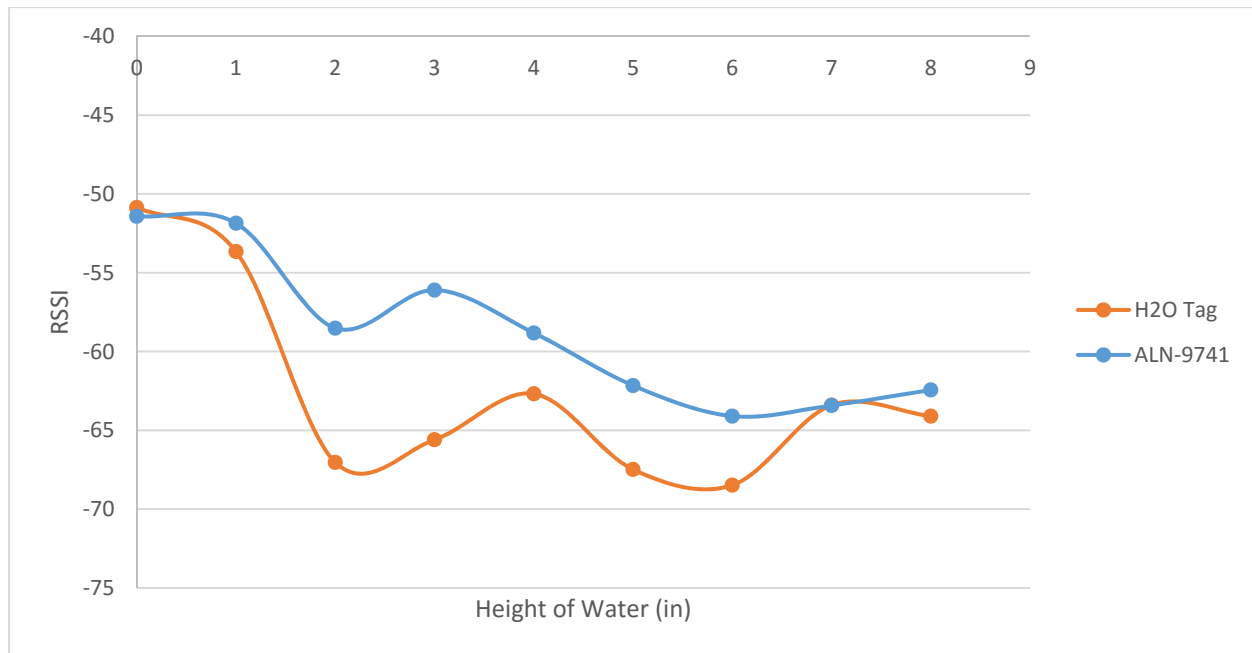


Figure 12: RSSI value measured using the ALH-9011 reader for both the H2O prototype tag and the ALN-9741 as water was poured on top of the tag in a container.

#### 2.2.4 Soil and Water Depth Combination

Once both the water and soil tests had been completed separately, a combination test was conducted. Initially, four inches high of sand was added to the same container used in the water depth and soil depth experiments. Then the ALN-9741 tag was centered in the container and buried under an additional four inches of sand. For the data collection on this test, five RSSI readings were taken from 1, 3 and 5 feet above the top layer of sand. Once all fifteen readings were taken, 2000 mL of water was added to the container to simulate half-saturated soil. An additional fifteen readings, under the same circumstances, were taken. Finally, an additional 2000 mL of water was added to the container to simulate full-saturation, and readings were once again recorded. The results from this test can be seen in Figure 13 below.

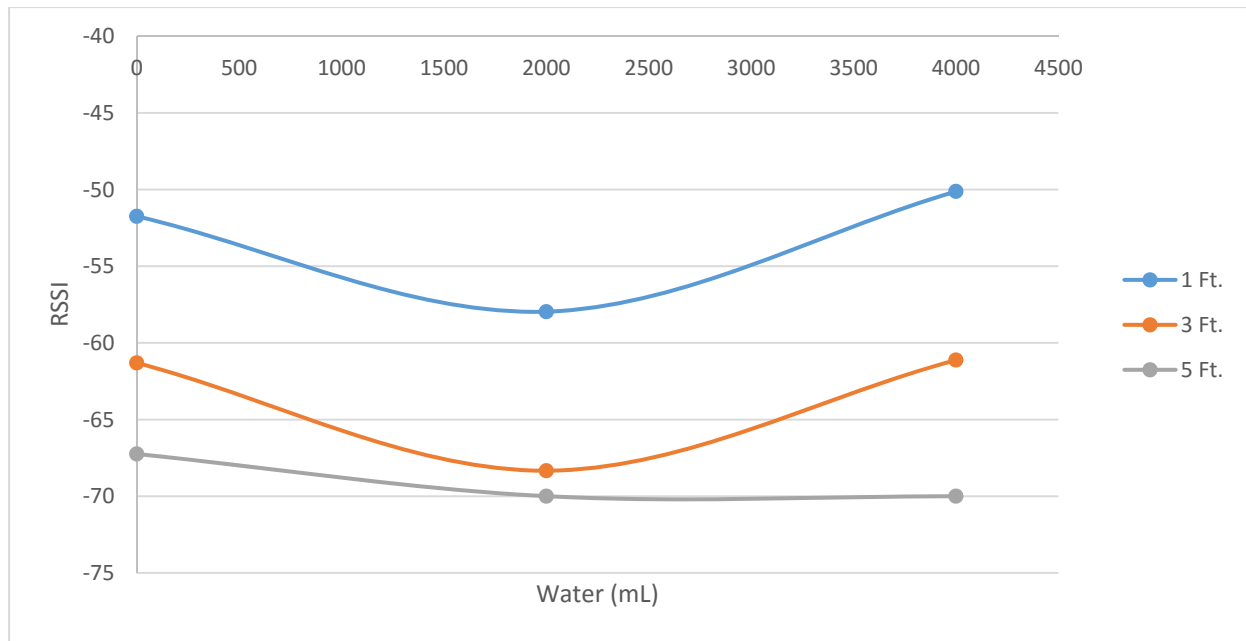


Figure 13: RSSI value measured using the ALH-9011 and the ALN-9741 for different saturation levels and varying distances above the tag.

For the ALH-9011, the Geiger application used for to measure RSSI values topped out at -70, so the values for both 2000 mL and 4000 mL of water measure five feet away we both plotted at the make value. There is a noticeable decrease in the RSSI value as the distance increase. However, as the sand goes from half-saturation to full-saturation, there is an increase in RSSI values.

### 3.0 Conclusion

Based on evidence from the experiments, the attenuation of radio waves through soil fluctuates with the amount of moisture. However, the radio signal strength indicator appears to be inconsistent. This indicates that even though there is an effect of the moisture on the strength of the signal, the technology isn't currently advanced enough for this application.

Moving forward for better results, RSSI values must have less noise for accurate and precise results. After the technology advances, then more experiments can be conducted to correlate the radio signal strength to soil moisture. There will still be some variations because the soil sensors are only able to record soil moisture within a small radius surrounding the sensor. However, the RFID tags are reporting the soil moisture for all soil above it as well. This results in some errors as the signal is not simply taking measurements from one location but is passing through layers of material. RFID tags provide temporal and spatial data at a cheaper, more energy efficient than any other current practice.

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